Carbon Sequestration Risks and Risk Management

P.N. Price, T E. McKone, and M.D. Sohn

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

Berkeley, California 94720

Abstract

This section summarizes the risk assessment approaches and risk management methods that can be applied to study geologic carbon sequestration in California, including CO_2 capture, transportation and storage operations. Risk assessment and risk management concepts are introduced and applied. Known hazards from carbon sequestration are discussed individually, and risk reduction options are presented. Human exposure limits, pathways for human and environmental exposure during operations and post-operations, and how risks change over the time scales associated with storage as the CO_2 migrates and reacts in the subsurface environment, are also discussed.

Table of Contents

1.0 Introduction

The intent of geologic carbon dioxide (CO_2) sequestration, also known as "geologic carbon sequestration," is to prevent anthropogenic CO_2 from entering the atmosphere, thereby maintaining acceptable levels of atmospheric CO_2. Ideally, the CO_2 will be safely transported to sequestration sites and injected deep underground, where it will be permanently trapped, with no negative impact on the terrestrial environment or on underground resources such as groundwater or fossil fuel deposits.   In practice, carbon sequestration will be neither perfectly effective nor risk-free. There are risks associated with geologic carbon sequestration, and evaluation of these risks will be important for making decisions concerning where and how sequestration should be performed.

The goal of a risk *assessment* is to quantify the likelihood of harm (or loss) and to present the results in a format that assists decision makers who must act to tolerate, mitigate, or eliminate the potential harm. The goal of risk *management* is to establish the practical significance of the assessed risks, compare the costs of reducing these risk to benefits gained, compare the risks to the societal benefits derived from incurring the risk, and to establish political and institutional processes of reducing risks. Further discussion of risk assessment, risk management, and their relationships to policy decisions can be found in Kahneman et al. (1982), Ruckelshaus (1983), NRC (1984 and 1996), and Kammen and Hassenzahl (1999).

This section summarizes the risk assessment approaches and risk management methods that can be applied to study geologic carbon sequestration in California, including CO_2 capture, transportation and storage operations. It includes consideration of human exposure limits, pathways for human and environmental exposure during operations and post-operations, and how risks change over the time scales associated with storage as the CO_2 migrates and reacts in the subsurface environment.

2.0 Background on Risk Assessment and Risk Management

To understand and manage the threats posed by a technology, decision-makers often rely on risk *assessment* as a process to identify the likelihood that some action (or inaction) will result in harm, and rely on risk *management* to communicate and/or reduce the risks. We provide an introduction to both concepts as they relate to carbon sequestration, in the following subsections. McKone, 1996 provides more detail if desired.

2.1. Risk Assessment

Risk assessment requires not simply an evaluation of what deleterious effects are *possible*, but also an assessment of the likelihood of these effects.

In an early and widely cited paper, Kaplan and Garrick (1981) noted that a risk assessment should address three questions:

1. What can go wrong?
2. How likely is it to happen?
3. What are the consequences?

The first question is answered by a hazard assessment: defining accidents, failures, or exposure sequences beginning with their initiating event, followed by any chain of events that either mitigate or facilitate a progression toward harm. For engineered systems this is commonly called an accident or failure sequence. In toxicology this is the source-to-dose-to-effect sequence, in which a chemical release leads to exposure, which in turn leads to an internal dose, which in turn causes disease through a mechanism of action. The answer to the second question is the frequency or probability that the specified sequence will actually occur. The third question is addressed by the end state – if the sequence occurs, what is the ultimate impact? – which expresses consequences as some number of fatalities, injuries, or diseases in the human health risk assessment; as the expected effect on species or ecosystems in ecological risk assessment; or as dollars lost in a financial risk assessment.

The Society for Risk Analysis (SRA 2007) has broadly defined risk as the "potential for realization of unwanted, adverse consequences to human life, health, property, or the environment; estimation of risk is usually based on the expected value of the conditional probability of the event occurring times the consequence of the event given that it has occurred." Posing risk in this fashion has led many practitioners to quantify risk as a summation over a range of potential event sequences of the consequences from that sequence multiplied by the probability of the sequence. This approach results in an operational or instrumental definition of risk as the expected value of a probability distribution of impacts. From this approach Kaplan and Garrick (1981) define risk as a "triplet" set composed of sequences, probabilities, and consequences. This gives rise to one way of defining risk quantitatively: risk is the "expected value of an undesirable consequence":

$$Risk = \sum_{i=1}^{n}(prob_i)(consequence_i) \qquad\qquad (5\text{-}1)$$

Here, i is the ith hazard, and $prob_i$ and $consequence_i$ are the probability and consequence (over some time interval) associated with the ith hazard. When actuarial data are available, the probability over time becomes the frequency of the ith sequence. For technical systems such as an aerospace vehicle, a chemical process plant, a civil structure or a nuclear power plant, risk may then be expressed as an "average annual probability of consequence" such as mission failure rate, or chronic exposure rate, or core damage frequency, or acute fatality rate.

The expression of risk in terms of the expected value of undesirable consequences, as in Equation 5-1, is not the only method to define or quantify risk, and is often not adequate if used alone in making policy decisions. Two policies or actions might have equal risk as defined in this way, but still be very different in important ways. For example, Policy A might be guaranteed to kill 100 people each year, while Policy B has, each year, a 1/1000 chance of killing 100,000 people. Both of these have the same "risk" as defined by Equation 5-1 (an expected value of 100 deaths per year) but they might not be seen as equally undesirable. Another drawback of quantifying risk as a single number is that the number sometimes depends on quantities that are very hard to estimate, such as the odds of an extremely unlikely but extremely costly or dangerous event occurring. For example, it may be almost impossible to quantify either the (tiny) probability of a major earthquake induced by CO_2 injection, or the

(enormous) cost if it occurs, but the "risk" as defined by Equation 5-1 might depend strongly on the product of these two numbers.

Rather than attempt to quantify risk with a single number, as in Equation 5-1, it can be better to generate more sophisticated summaries of risks, such as summaries of the "best plausible case" and "worst plausible case," or statistical distributions of cost and hazard estimates.

Risk assessment starts with hazard identification, which refers to identifying all possible hazards without focusing on the likelihood of harm or the extent of damage. After hazard identification, the next step is risk characterization. Risk characterization involves detailed assessment of each identified hazard in order to determine the risk posed by the hazard. Risk characterization includes three principal elements: (1) identify all of the scenarios in which the negative effects of the hazard would be realized, (2) quantify the negative consequences associated with each scenario, and (3) assess the magnitude and sources of uncertainty that limit the accuracy of the estimates in parts (1) and (2).

2.1.1. Exposure Assessment as Part of Risk Assessment

As will be discussed in Section 5.4, one of the hazards associated with CO_2 sequestration is exposure of people, animals, or plants to harmful levels of CO_2. As applied to effects of exposure from a toxic agent, hazard identification comprises identifying sources and pathways, and estimating environmental concentrations in exposure media such as ambient air and indoor air. Risk assessment requires the additional steps of quantifying the probability that the hazard will be realized, and quantifying the resulting exposures; this is called "exposure assessment." Risk assessment further includes quantifying a dose-response function and using it to determine the negative effects of the predicted exposures.

Exposure assessment is an important component of a risk assessment that addresses residential or occupational contacts to routine or accidental releases of harmful agents. Exposure assessments provide an evaluation of who is exposed and at what levels. This includes information on the intensity, frequency, and duration of human exposures to a harmful substance as a result of normal or accidental conditions. An exposure assessment develops information for real-world scenarios to estimate the levels at which human populations—children, workers, the total population, the most exposed individual, or other groups—may be exposed for comparison with the dose levels developed in the dose-response analysis. If CO_2 sequestration were to take place at a specific location and in a given manner, what exposures would be expected for animals, plants, and people in the area, now and into the future?

Dose-response assessment for a particular substance evaluates data on the relationship between the dose of the substance administered or received and the level of a specific adverse effect that is imposed on the receptor population in response to that dose. How increases in dose (as a result of exposure) to the agent correspond with adverse health responses is the critical question. To develop dose-response relationships, risk assessors review studies of test animals or people exposed through time and try to ascertain how the accumulated dose links with patterns of adverse health effects. There are key uncertainties that arise in this effort. The inference of low-dose effects from high-dose experiments is called the low-dose extrapolation

problem. There are also the problems of extrapolation from animals to humans and of accounting for variations in human susceptibility. Statistical and mathematical models are often used to quantify key processes as part of dose-response assessment. This step may also involve an assessment of the variations in response such as differences in susceptibility between young and old people. Advances in ways to model differences between test animals and people in terms of body weight, metabolism, breathing rates, blood flow and other biological parameters has allowed more precise comparisons to be made between species. In the context of carbon sequestration, the dose-response assessment step attempts to determine the relationship between the magnitude of exposure to CO_2 and the probability and severity of adverse effects. If a plant, animal, or person is exposed to a given concentration over a given time period, what (if any) negative impacts will result?

A great deal of information is available concerning CO_2 toxicity; some of the relevant material is summarized in a later section of this report.

2.2. Risk Management

Once the risks associated with an action have been identified and quantified, the decision maker or regulator develops a basis for evaluating these risks and then, as necessary, developing and carrying some actions to communicate and reduce the risks. The goal of the risk management process is to establish the significance of the estimated risk, compare the costs of reducing this risk to benefits gained, compare the estimated risks to the societal benefits derived from incurring the risk, and carrying out the political and institutional process of reducing risk. There are four types of analyses that are commonly used in the risk management process: risk-benefit, cost-benefit, risk-risk, and cost-effectiveness analyses. A risk-benefit analysis provides a comparison of the risks added by an activity to the concurrent benefits (usually economic) provided to society. A cost-benefit analysis relates the financial cost (in dollars) of reducing risk to the benefits (in equivalent dollars or an appropriate surrogate) gained by reducing risk. A risk-risk analysis establishes the significance of an estimated risk by comparing it to some other acceptable or familiar risk such as those associated with background exposures, household accidents, occupational hazards, natural occurrences, etc. A cost-effectiveness analysis is used to compare risk reduction per unit cost among several options for dealing with the same risk.

3.0 The Problem of Uncertainty

All risk assessments are conducted without complete and perfect knowledge. Addressing uncertainty is perhaps foremost among the recurring themes in risk assessment. In addressing uncertainty, it is important to distinguish between random variations (or variability), and lack of knowledge. Risk assessment, as currently conceived and practiced, accounts for these two types of uncertainty (NRC 1996), referred to as aleatory (random variations and chance outcomes in the physical world) and epistemic (lack of knowledge about the physical world). More research (both observational and theoretical) can reduce epistemic uncertainty, but aleatory uncertainty can only be better characterized, but not reduced, with more research.

An effective and useful risk assessment poses a challenge to the assessor in many ways. Consider as an example, the process of characterizing risk to hazardous chemicals. We are

uncertain about whether we have captured all of the most important "events" in our portfolio of release scenarios. Even for scenarios that are well established, sources are not well characterized, and exposure pathways are complex and vary substantially among individuals and among different populations in terms of age, location, and socioeconomic status. Quantifying the relationship between chemical exposure and the probability of an adverse health effect is also complicated by the need to extrapolate effects from high doses to lower doses and animal studies to humans. Finally, little is typically known about inter-individual differences in susceptibility. These factors make it difficult to establish both the probability and magnitude of consequences for a given exposure scenario. They also may complicate determining risk as a single number or even as a single range of numbers. As a result, developing quantitative risk estimates in the face of substantial uncertainty, and appropriately characterizing the degree of confidence in the results are recurring themes in health risk assessment as well as other fields of risk assessment—ecological risk, accident risks, global climate change, economic risk, etc.

Decision makers often operate under the premise that, with sufficient funding, science and technology will provide an obvious and cost-effective solution to the problems of protecting human health and the environment. However, in reality there are many sources of uncertainty and variability in the process of human-health and ecological risk assessment. Many of these uncertainties and variabilities are not reducible. Effective policies are possible under conditions of uncertainty, but such policies must take the uncertainty into account. There is a well-developed theory of decision making under uncertainty, which has been described in Chernoff and Moses (1959), Lindley (1985), and Berger (1985) among others.

One often-used method for addressing uncertainty in risk assessments is the compounding of upper bound estimates in order to make decisions based on a highly conservative estimate of risk. Such an approach is contrary to the principles of decision making under uncertainty (as described in the texts cited above). This latter approach leaves the decision maker with no flexibility to address margins of error; to consider reducible versus irreducible uncertainty; to separate individual variability from true scientific uncertainty; or to consider benefits, costs, and comparable risks in the decision making process.

The principles of decision making under uncertainty are not necessarily complex. Often the principles of such decision making are simply common sense. But in any issue involving uncertainty, it is important to consider a variety of plausible hypotheses about the world; consider a variety of possible strategies for meeting our goals; favor actions that are robust to uncertainties; favor actions that are informative; probe and experiment; monitor results; update assessments and modify policy accordingly and favor actions that are reversible (Ludwig et al. 1993). In order to make risk assessment consistent with such an approach, it should incorporate a formal quantitative treatment of uncertainties in the risk characterization step.

In its draft report on treatment of uncertainty in exposure assessment, the International Program on Chemical Safety (IPCS 2007) proposed four tiers for addressing uncertainty in exposure assessment ranging from the use of default assumptions to sophisticated probabilistic risk assessment. The IPCS tiers are as follows:

Tier 0: Default assumptions: single value of result, no uncertainty characterization.

Tier 1: Includes qualitative but systematic identification and characterization of uncertainties

Tier 2: Includes quantitative evaluation of uncertainty making use of bounding values, interval analysis, and sensitivity analysis.

Tier 3: Includes probabilistic assessments with single or multiple outcome distributions reflecting uncertainty and variability.

Although these tiers were developed for chemical safety, they provide a good basis for discussing uncertainties in other contexts as well, including carbon sequestration.

Even a Tier 1 analysis may be sufficient in some cases: if it is clear that a given risk is "extremely low" then it may be deemed acceptable without the need to quantify it, while an "extremely high" risk may be unacceptable.

Tier 3 risk assessments are usually expected to be better – more informative and more accurate – than lower-tier risk assessments. In practice, however, the added complexity of Tier 3 approaches does not always lead to better decision making. Uncertainties in the physical or statistical models (or parameter values) used in a Tier 3 analysis may be so high that there is little point in proceeding past a Tier 2 analysis. Either a Tier 2 or Tier 3 analysis requires attempting to identify all significant hazards, to quantify the probability of occurrence, and to determine which hazards contribute the most to the risk; as such, either can be extremely valuable to decision-makers.

Risk managers must consider their role in reducing or incorporating uncertainty as well as in managing risk. This includes allocating resources among (1) investing to collect, store and manage information; (2) investing to improve the knowledge base (i.e., to generate new knowledge); (3) formalizing processes used to collect, use and process information; (4) formalizing processes to calculate and communicate uncertainty; and (5) adjusting the risk assessment process to mitigate the practical impact of uncertainty.

4.0   Carbon Sequestration Hazards

Now that we have discussed the risk assessment and risk management in general terms, we move on to the specifics of assessing risks from geologic carbon sequestration. The potential hazards from carbon sequestration are economic, ecological, and human health-related, and have been studied extensively by Benson et al. 2007 and the IPCC 2005 (especially Chapters 5 and 6). Of the hazards reported, those pertaining to sequestration in California include:

1. Injury, death, or ecosystem damage caused by exposure to harmful levels of CO_2;

2. Damage to groundwater resources through direct contamination with CO_2, or contamination by leaching of toxic material from surrounding rock, due to acidification of water by dissolved CO_2;

3. Damage to mineral resources through (a) contamination of natural gas or oil by CO_2, (b) pressure-induced migration of mobile fossil fuels in a way that complicates extraction or renders it infeasible, (c) sorption of CO_2 into coal, or (d) alteration of economically important ores, minerals, gravels, etc., by CO_2 or by acidified water;

4. Induced or enhanced seismicity due to increased fluid pressure deep underground;

5. Injury or death to workers through heavy-machinery accidents and other industrial accidents not covered in item 1 above.

The risks associated with the hazards listed above are not fixed quantities: they depend on what sites are used for sequestration, on the pipeline technologies and operating practices used to detect and fix leaks, and so on. Quantitatively characterizing the risks associated with specific sequestration sites, pipeline routes, and management strategies will be an important challenge for risk assessors if widespread carbon sequestration is to become a reality.

Quantitative assessment of carbon sequestration risk will not be starting from scratch. For example, CO_2 pipelines already exist (mostly to provide CO_2 for enhanced oil recovery), and natural gas and other types of pipelines are extensively used. Some large-scale carbon sequestration projects already exist and are the source of useful data. Underground injection has also long been used for pollutants other than CO_2, and for natural gas storage. And injection of CO_2 for enhanced oil recovery operations closely parallels injection for carbon sequestration. In short, there is already a fair amount of real-world experience that can help to quantify the risk associated with the hazards identified above.

4.1. What Can Go Wrong?

CO_2 sequestration will involve large construction projects. CO_2 extraction equipment will be installed at power plants; pipelines and pumping stations will be built; and injection wells and monitoring wells will be drilled. All of these industrial construction and drilling operations will involve accident risks to workers. We do not consider these risks in this report because they are well understood and are not unique to carbon sequestration.

The previous section discusses some of the hazards associated with geologic carbon sequestration. The next step is to identify scenarios – failure mechanisms – that could lead to those hazards being realized. As with hazard identification, the literature on this topic has identified mechanisms and scenarios for how CO_2 transport and storage could cause harm to humans, to ecosystems, and to resources; see Benson et al. 2007 and IPCC 2005. We now consider some of these hazards in more detail. :

1. Leakage of CO_2 from *pipelines or pumping stations* to the surface or shallow subsurface could lead to damaging or lethal effects on people, animals, and plants through asphyxiation or toxicity.

2. Leakage of CO_2 from *geologic sequestration sites* to the surface or shallow subsurface could lead to damaging or lethal effects on people, animals, and plants through asphyxiation or toxicity:

a. Gradual leakage could allow CO_2 to build up in topographic depressions or in enclosures such as basements.

b. Gradual leakage of CO_2 from geologic storage sites into lakes could create a deep-water layer of water that is saturated CO_2; "overturning" of the lake could rapidly release this water to the atmosphere.

- Leakage of CO_2 from geologic repositories into groundwater could degrade water quality, either directly or by acidifying the water so that it leaches toxic compounds out of rock or soil.

- Leakage of CO_2 from geologic repositories into fossil fuel assets such as natural gas or oil deposits could increase the costs of recovering or refining those assets or could render them unusable.

- Leakage of CO_2 from geologic repositories could be so large that there is little or no reduction in atmospheric CO_2 concentrations compared to the no-sequestration case.

- Injection of CO_2 into porous rock at high pressure could induce fracturing, which could (a) increase permeability, thus increasing the leakage risks listed above, or (b) "activate" otherwise dormant faults, inducing potentially damaging earthquakes.

Items 1 and 2 both involve toxic effects from CO_2, so we begin by summarizing the risks from CO_2 exposure.

4.1.1. CO_2 Dose-Response Relationship

Carbon dioxide occurs naturally, and all animals (including humans) have a long evolutionary history of exposure to several hundred parts per million (ppm) of CO_2 in air. The current atmospheric concentration of CO_2 is about 380 ppm. The atmospheric concentration is expected to increase over the next hundred years or more due to continued fossil fuel burning, and is likely to exceed 600 ppm by the end of this century.

Humans, like other animals, are tolerant of CO_2 concentrations much higher than normal without known ill effects. CO_2 concentrations above about 800 ppm can lead to a perception of stale air, but without apparent physiological effects. Some people (such as submarine sailors) have been exposed to 1000 ppm (i.e. 0.1% CO_2) for several weeks, again with no known effects; however, most of these highly exposed people have been healthy young males, and one might speculate that some subgroups, such as people with decreased lung function, might be more susceptible to harm under these conditions.

From about 1000 ppm, to 1500 ppm, CO_2 is a respiratory stimulant – i.e. it causes an increased breathing rate – but has no other known physiologic effects. From 1500 ppm to 3000 ppm, the CO_2 concentration in blood increases above normal levels, making the blood acidic (a condition called acidosis). A significant increase in respiratory rate, and some discomfort, set in at about 30,000 ppm (3%) of airborne CO_2, and above 5% the effects become severe and loss of consciousness can occur.

Benson et al. (2007) note that "Experiments conducted on a group exposed to up to 3% CO_2 for many weeks and short-term exposures to even higher concentrations have shown that all effects are reversible except for prolonged coma, the consequences of prolonged hypoxia (lack of

oxygen), and death. Loss of consciousness occurs within several breaths and death is imminent at concentrations above 25 to 30%. Deaths from catastrophic releases of CO_2 are known from industrial accidents and natural disasters."

Federal occupational safety and health regulations limit workplace exposure to an average of less than 5000 ppm (0.5%) for a 40-hour work-week.

As for ecosystem effects, Benson et al. (2007) note that "Ecosystem impacts from exposure to elevated concentrations of CO_2 are poorly understood. Plants in general are even more tolerant than invertebrates to elevated CO_2, so any small-scale, short-term gas leaks would have minimal impacts. Persistent leaks, in contrast, could suppress respiration in the root zone or result in soil acidification, and catastrophic releases could certainly kill vegetation as well as animals. Most of the controlled experiments have focused on the moderate increases in CO_2 concentrations that are expected to occur due to atmospheric buildup of CO_2 from the continued use of fossil fuels or that stimulate plant productivity in greenhouses. The studies have shown that moderate increases in CO_2 concentrations stimulate plant growth, while decreasing the loss of water through transpiration. At the other end of the scale, tree kills associated with soil gas concentrations in the range of 20 to 30% CO_2 have been observed at Mammoth Mountain, California, where volcanic out-gassing of CO_2 has been occurring since at least 1990. Little information is available in the intermediate range of 2 to 30%. In addition, information on the tolerance of aquatic ecosystems to short-term, catastrophic releases was not found and may need to be researched."

4.1.2. Hazard 1: Exposure Due to Pipeline Leaks

CO_2 from power plants or other industrial operations is likely to be transported to storage sites via pipelines. Above-ground or near-surface CO_2 pipelines provide the most direct route to harmful human exposure or to deleterious impacts on animals and plants by producing a local high concentration of CO_2 and generating exposures sufficient to harm or kill people, plants or animals. See Gale and Davison (2003) for more information and discussion.

While an important risk, precautions that are common for existing pipelines for distributing materials that are far more dangerous can be taken to minimize the likelihood of a major pipeline breach. Moreover, pipeline distribution systems, including CO_2 pipelines, have a fairly good safety record. Long-distance CO_2 pipelines in the U.S. total about 2600 km and produced no injuries or fatalities over a thirteen-year period studied by Gale and Davidson (2002). Geologic carbon sequestration would require building many more pipelines, some of which would likely pass through or near densely populated areas since they must originate at power stations, so past history with CO_2 pipelines does not guarantee that future pipelines will be equally safe.

Natural gas pipelines are of course different from CO_2 pipelines in several significant ways, the most important of which is that natural gas is highly flammable when mixed with air. There are 295,000 miles of natural gas transmission pipelines in the U.S., and about 1.4 million miles of distribution pipelines. According to the Pipeline and Hazardous Materials Safety Administration, during the 10-year period from 1994-2003 (inclusive), 795 natural gas pipeline

accidents resulted in 26 fatalities, 97 injuries, and $256 million property damage. Most of the fatalities and injuries were due to fires or explosions associated with pipeline leaks, almost a third of which are due to excavation damage. Notably, 20% of incidents were due to corrosion. Since CO_2, in the presence of elevated humidity, is more corrosive than natural gas, corrosion may be a significant failure route for CO_2 pipelines. Conventional pipelines for most materials use carbon-manganese steel, which is not corroded by CO_2 if humidity in the pipeline is low, but which needs to be replaced by stainless steel if the humidity is high. Stainless steel is very expensive, so it will likely be economically important to dry the CO_2 before transport, to avoid the need for stainless steel.

Pipeline damage may occur more frequently in California than elsewhere because of seismicity. Outright breakage of pipelines during earthquakes (or other land movements such as landslides) that cause large ground movements is likely to be rare. More commonly, gradual shifts in the ground may cause stresses that lead to small leaks.

A small pipeline leak could cause harm if the CO_2 pools in a topographic depression. The concentration of CO_2 will be determined by the competition between the rate that CO_2 leaks from the pipeline and enters the depression, and the rate that CO_2 escapes the depressed area due to wind. If the release is very small or if wind mixes the depressed area significantly and regularly, the concentration in the area will be well below a level of concern. Risks from pooling apply to other types of dense gases in pipelines, so analysis of this risk should include examination of existing data on other pipelines.

A large pipeline leak resulting from a major rupture would release a large quantity of CO_2 very quickly. The resulting plume could flow downhill from the release point, endangering people and animals below. Such a release would be short-lived and would be rapidly detected by pipeline monitoring (and perhaps immediately apparent to people in the vicinity as well). As with the risk of a small leak, the risk of a large leak is not unique to CO_2, so data on other types of pipelines can provide useful quantitative information on the statistical distribution of leak sizes and frequencies that can be expected.

Steps can be taken to minimize risks from CO_2 pipelines (as from any hazardous material pipelines). Steps include:

1. Site pipelines away from populous areas when possible;
2. Avoid running pipelines near homes in sheltered, populated valleys where leaking CO_2 could accumulate to dangerous levels;
3. Monitor pipelines regularly for corrosion;
4. Monitor constantly for leaks;
5. Install safety valves to shut off the pipeline in the event of a large leak;
6. Consider adding odorant to CO_2, as is done with natural gas, to allow people to notice small leaks. We are unaware of studies on the costs or effectiveness of odorants for CO_2; given CO_2's low toxicity it is questionable whether this step would be worthwhile in

general. It might be useful in special cases, such as pipelines that necessarily pass through populous areas.

4.1.3. Hazard 2: Exposure Due to Leakage from Geological Storage

Risk from slow, steady discharge

Releases of CO_2 that are much too small to cause widespread death or injury can still cause acute local problems, including human fatalities. Human, animal, and plant fatalities from CO_2 have occurred near hot springs and fumaroles. The area around Mammoth Mountain, California provides a good illustration.

Mammoth Mountain is a young volcano. In 1990, following a series of small earthquakes the previous year, CO_2 began leaking upwards along faults from a natural subterranean reservoir of CO_2. The amount of CO_2 leakage has been estimated at about 300 tons per day for the entire fault system, which covers several square miles, but the leaks are concentrated in certain areas that therefore have locally high CO_2 concentrations. The high concentration of CO_2 in soils in some areas has killed over 100 acres of trees, and the airborne concentrations are high enough to endanger animals or people in depressions and enclosed spaces. Three ski patrol members were killed in 2006 when they fell into a depression in the snow that contained a very high concentration of CO_2.

Another instructive example of CO_2 leakage to the surface is provided by the "Crystal Geyser" in Utah. Crystal Geyser is an oil exploration shaft in Utah that was abandoned, without being properly plugged, around 1940 after encountering a natural pressurized CO_2 reservoir. It erupts like a geyser every day or two, and can eject up to 40 tonnes of CO_2 mixed with water during a two-hour eruption. Terrain near the geyser is fairly flat, and does not have depressions that tend to accumulate CO_2.   Visitors to the site during eruptions have not experienced ill effects, even when standing under the ten-foot-high jet of carbonated water ejected from the geyser. However, calculations (Bogen et al. 2006) suggest that in some unusual weather conditions, CO_2 concentrations very close to the ground could reach lethal levels, thereby injuring or killing small animals or potentially prone animals or people (e.g., campers).

The examples discussed above concern leakage to the open air, but leakage directly into structures is also possible. Leakage from a geologic sequestration site directly into a basement, for example, could lead to a high concentration of CO_2; in fact, since wind would not be able to cause mixing that would dilute the CO_2, the concentration in a basement would be higher than would result from the same leakage rate into an outdoor depression.

As the Mammoth Mountain and Crystal Geyser examples indicate, leakage can occur via naturally occurring faults and fractures, and also via manmade boreholes. Abandoned wells are thought to present the most important risk of leakage from geologic carbon sequestration sites, since (if not properly plugged) they can provide a very low-resistance pathway from deep underground to the surface. Moreover, abandoned wells are likely to be present in some of the geologic formations that are attractive for carbon sequestration, since some of the same geologic

features that make a site a likely location to find natural gas or oil also make it attractive for sequestration. Abandoned oil and gas fields are likely candidates as carbon sequestration sites because they have already proven to be able to retain fluids under pressure for millions of years.

A crude calculation shows that risk of acute injury due to slow leakage from a geologic sequestration reservoir cannot be completely ruled out. Consider sequestering emissions from a 1000 MW coal-fired power plant, for 10,000 days (about 27 years). At a rate of 30,000 tonnes per day, the total amount of CO_2 pumped underground is 300,000,000 tonnes. If this amount leaks out uniformly over a period of 300,000 days (820 years), this corresponds to a leakage rate of 1000 tonnes per day, or about three times the estimated emissions at Mammoth Mountain. This calculation assumes, unrealistically, that all of the gas leaks out, with none of it trapped for a long time in geologic formations or groundwater, and it ignores the fact that the leakage rate would diminish with time as the driving pressure dissipates. Still, it suggests that if the geologic sequestration fails so that a substantial fraction of the sequestered CO_2 leaks to the surface within a few hundred years, the rate of leakage to the surface could be high enough to cause severe local impacts, including potential loss of life.

Possible actions to reduce risks from leakage include:

1. Select sequestration reservoir sites that are likely to retain most of their CO_2 for at least thousands of years, not just hundreds.
2. Locate and plug abandoned boreholes, and monitor them for leakage.
3. Select sites that are not near large population concentrations.
4. Monitor sites for leakage and halt operations, or reduce the total amount of CO_2 sequestered, if an unacceptably high leakage rate is detected.

Risk from a fast, large discharge

Although natural underground CO_2 reservoirs exist throughout the world in volcanically active areas, there are very few known instances of rapid discharge of large amounts of CO_2. Large-scale fatalities from such releases are extremely rare, but they have occurred. We now discuss a famous example, which is the most damaging on record.

In 1986, over 1700 villagers and 3500 cattle living near Lake Nyos in Cameroon were killed when the lake suddenly released about 1.4 million tonnes of CO_2 (1 tonne = 1 metric ton = 1000 Kg, approximately equal to 1 ton). For comparison, a 1000 MW coal-fired power plant emits about 30,000 tonnes of CO_2 per day; the Lake Nyos release represented about 50 days of emissions from a large power plant.

The Lake Nyos event occurred as follows. CO_2 from volcanic activity had accumulated for decades in the cold water deep in the lake. At the high pressures deep in the lake, the CO_2 remained in solution (i.e. dissolved in water), but water that moved upwards by even a small amount experienced lower pressure, so that CO_2 came out of solution and formed bubbles, just as occurs when a can of soda is opened. These bubbles then rushed to the surface of the lake, drawing more of the deep, saturated lake water up with them and thus continuing the release.

CO_2 is heavier than air. The CO_2 flowed down the valley below the lake, smothering several villages.

The event that triggered the initial upward movement of saturated water is not known, but may have been an underwater landslide or an earthquake. Once the deep water is close to full saturation, even a small disturbance can trigger a release, and future releases at Lake Nyos are inevitable unless mitigation is performed: the lake still contains an estimated 300,000 tonnes of CO_2, and natural (volcanic) CO_2 enters the lake at an estimated 5000 tonnes per year.

The CO_2 release rate at Lake Nyos, between 1.2 and 1.6 million tonnes of CO_2 released to the air within hours, was vastly higher than could occur by direct leakage from a geologic sequestration site to the earth's surface: the lake had accumulated CO_2 that leaked from underground over many decades. It is possible for a Lake Nyos-type disaster to occur due to leakage from a geologic sequestration site if a geologic CO_2 source leaks into a lake under special conditions. These conditions include: (1) the sequestration reservoir would have to fail, so that CO_2 leaks at a fairly rapid rate into a deep portion of the lake, through a fracture or well that connects to the underground source, (2) the lake is vertically stratified so that deep water does not circulate to the surface and thereby dissipate its CO_2 as quickly as it accumulates, and (3) the lake is deep enough that a very large amount of CO_2 can accumulate before a spontaneous release event. A release would cause a large number of human fatalities only if (4) there is a substantial human population near the lake, near or below the lake's surface elevation.

Given the special conditions that are required for a Lake Nyos-type event, the risk of such an event from a failed CO_2 sequestration site is low even if no special precautions are taken. For example, there are only three known sites in the world where deep lake water is saturated with CO_2 from natural sources.

Several steps can be taken to minimize the chance of a Lake Nyos-type event:

1. Select sites that, even if they leak, will not leak rapidly into deep lakes. The proximity of the lake to the geologic reservoir, the presence of faults under the lake, and the depth of the lake should all be taken into account.
2. Select sites that are not near large population concentrations.
3. If a sequestration site is located near a large, deep lake into which leakage is possible, occasional monitoring of the CO_2 concentration deep in the lake should be performed. Mitigation is possible: an inexpensive, self-perpetuating system has been operating at Lake Nyos since 2001, for example.

4.1.4. Hazard 3: Leakage from Geological Storage to Groundwater

A fraction of the CO_2 injected into the ground will readily be dissolved into water, including pore water between grains or minerals in geologic formations. In many cases, dissolution of CO_2 into water is desirable, and some sequestration projects (including the Sleipner project in the North Sea) deliberately inject CO_2 into deep saline (salt-water) reservoirs. The CO_2-saturated brine is expected to become denser than the surrounding unsaturated brine and will therefore sink, reducing the risk of upward migration. The worldwide storage capacity of deep saline

formations probably exceeds 1000 Gigatonnes of CO_2 and may exceed 10000 Gt, and is probably much larger than the storage capacity of depleted oil and gas fields.

Although often desirable, dissolution of CO_2 into water can also be problematic. The water will be acidified, which may allow it to degrade geologic formations which may toxic compounds that leach out. Water saturated with CO_2 is also not useful as drinking water. Over time, water contaminated with toxins or with CO_2 could migrate and contaminate groundwater aquifers or other resources.

Benson et al. (2007) note that "Industrial liquid waste disposal by deep-well injection was initiated in 1939. Since that time the practice has expanded so that now, nine billion gallons per year of hazardous, industrial and municipal wastes are injected into 485 Class I wells. In 1987, the cost of liquid-hazardous-waste disposal ranged from $49 to $207/ton. Early performance was mixed, with many examples of well failures and contamination of drinking water aquifers. Failures were attributed to (1) poor characterization of the confining units; (2) improper well completion techniques; (3) use of well construction materials that were incompatible with the waste streams and, consequently, corroded; (4) inconsistent or inadequate monitoring; and (5) leakage through abandoned wells. Because of these problems and the inconsistent approach to monitoring, progressively more stringent regulations were put in place to make the practice of industrial waste disposal by liquid injection safer. By 1988, the current set of regulations was put in place. Since then there have been no incidents of drinking-water contamination reported."

Contamination of drinking water with CO_2, or with metals or chemicals leaching out of rock due to CO_2 acidification of the water, could be very costly if the affected aquifer is used by a lot of people. There is unlikely to be a workable in situ mitigation strategy: once an aquifer is contaminated, it will remain so.

As the quotation from Benson et al. shows, experience with underground disposal of liquid chemicals provides useful information about the ability to assess geologic formations for sequestration potential, and the ability to seal wells. However, some of the information is not perfectly applicable to CO_2 because (1) the quantity of CO_2 that would be injected into sequestration sites dwarfs the amount of toxic material injected into waste storage sites; and (2) CO_2 is buoyant, whereas most toxic material injected into waste wells is approximately neutral. On the other hand, (3) CO_2 is far less toxic than most materials that are injected for hazardous waste disposal.

Several steps can be taken to minimize the chance of leakage to groundwater:

1. Select sites that are far from aquifers that are or may in the future be used for potable water.

2. Select sites that, even if they leak, will not leak rapidly to groundwater. The conductivity of the surrounding geologic formations, the proximity of the groundwater, and the presence of faults should all be taken into account.

3. If a sequestration site is located near an important groundwater aquifer, occasional monitoring of the CO_2 concentration deep in the aquifer should be performed.

4.1.5. *Hazard 4: Leakage from Geological Storage to Fossil Fuel Assets*

Much like hazards of leakage from geological storage to groundwater, underground injection of CO_2 at pressures substantially higher than formation pressures can lead to seepage to fossil fuel deposits along faults, fissures, or abandoned and unsealed wells. Largely an economic risk, CO_2 contamination may decrease the value of the fossil fuels owing to excessive costs for removing, or separating, CO_2 before the fossil fuel can be transported.

Human hazards and risks are largely secondary, incurred mostly from the steps taken to remove CO_2 from the fossil fuel prior to the latter's use. Separation, capture, storage, and re-sequestration each create hazards to human exposure and are described in the above sections.

The probability of leakage to a fossil fuel asset is likely to be similar to the probability of leakage to groundwater. Both hazards occur largely due to transport via unknown or newly created faults, or unknown and unsealed wells in the vicinity of the storage site and the fuel asset.

Possible actions to reduce risks from leakage to fossil fuels include:

1. Select sequestration reservoir sites that are likely to retain most of their CO_2 for at least thousands of years, not just hundreds.
2. Select sites that are not near fossil fuels assets.
3. Monitor sites for rapid leakage (e.g. along previously undetected faults) and halt operations, or reduce the total amount of CO_2 sequestered, if rapid leakage is detected.

4.1.6. *Hazard 5: Leakage Eliminates Benefits of Geological Storage*

Leakage, in addition to enabling the hazards discussed in the previous subsections, also returns carbon into the atmosphere. Since the whole point of carbon sequestration is to prevent CO_2 from entering the atmosphere for hundreds or thousands of years, leakage at a much faster rate would eliminate the benefits of sequestration. In fact, if the fraction of sequestered CO_2 that leaks within a few hundred years is very high (more than 70% or so) then sequestration could actually be worse than simply emitting the CO_2 to the atmosphere in the first place: additional CO_2 is produced in generating the energy needed for sequestration (for removal of CO_2 from the waste gas stream, for pipeline transport, and for pumping underground), so the total amount of CO_2 generated is higher if sequestration is performed than if it is not.

Inadequately sealed boreholes (from fossil fuel extraction or exploration) are thought be the most likely causes of unexpected leakage. Finding and plugging such holes will be a key part of any carbon sequestration project. Boreholes can be monitored to ensure that they are adequately sealed, and additional work can be performed if necessary to seal them better.

4.1.7. *Hazard 6: Induced Fracturing or Seismicity*

Geologic carbon sequestration requires injecting large quantities of fluid – supercritical CO_2 – under high pressure. The resulting stresses can fracture the surrounding rock. Highly porous rock is less likely to fracture than is low-porosity rock, since porous rock will allow more fluid

migration and thus relieve some pressure. Other factors affecting the probability of fracturing are the injection rate and the strength of the rock.

Pressure-induced fracturing may be irrelevant or may be important. If fracturing occurs in the rock formations that are intended to *confine* the CO_2 – typically the formations above the injection site – then containment may be lost and CO_2 may escape to contaminate groundwater, or may escape to the surface. If, instead, fracturing occurs in the formations that are intended to *store* the CO_2, then fracturing may be irrelevant, as long as the confining formations remain intact.

An additional hazard is *induced seismicity*: injection may promote earthquakes. Wesson and Nicholson (1987) noted that injection usually triggers activity in a seismically unstable area, rather than causing stable areas to become unstable. This makes sense because the forces of the pressurized fluids themselves are not large on a geologic scale, and cannot provide enough energy to cause a significant earthquake on their own. They can, however, trigger the release of energy already stored in a fault.

Sminchak and Gupta (2002) say that "While most seismic events triggered by deep well injection are too small to be noticed, moderate earthquakes have occurred due to injection activity. Most notably, two earthquakes with Richter magnitude of 5.1 and 5.2 were triggered in Denver, Colorado, in 1966." In 2007 a geothermal project in Basel, Switzerland, was put on hold (and could possibly be cancelled) after two small earthquakes (Richter magnitudes 3.1 and 3.4) were caused by injection of water into hot rocks at a depth of 5 km.

Possible actions to reduce risks from induced fracturing or seismicity are:

1. Choose sequestration sites to avoid formations or locations that are prone to fracture or earthquakes.
2. Set injection rates so that pressures remain below the fracture pressure of surrounding rocks.
3. Monitor for seismic activity and reduce injection rates if the activity is too extreme.

Some level of induced seismicity may be deemed tolerable by decision-makers, but gaining community acceptance may be challenging. For example, the occasional earthquake of Richter magnitude 2.5 would cause no damage and indeed would be unnoticed by many people, but might still prove psychologically unsettling to many people.

5.0 Discussion

Geologic carbon sequestration presents the opportunity to greatly reduce the rate of injection of CO_2 into the atmosphere, at relatively low cost compared to many other options. Geologic carbon sequestration also entails risk, and the risk is unknown and may possibly be large.

Risks can be limited or reduced. Pipelines can be built with automatic monitoring devices and shutoff valves; sequestration sites can be chosen that are away from highly populated areas, and/or are known to have contained naturally occurring natural gas for a long time; and so on.

Uncertainties can also be reduced. Sites can be investigated using seismic techniques or tomography methods to characterize likely leakage pathways; computer models can be improved to capture previously ignored phenomena or to incorporate higher spatial resolution; data from sequestration sites already in use can be used to better quantify geologic parameters and other quantities.

Reducing uncertainties does nothing in and of itself to reduce risks. However, quantifying risk is very important. Consider a sequestration site that is thought to be acceptable – i.e. the risk is below some target value – but this assessment is based on rather limited information. More information could discover previously unknown problems, such as faults or fractures, thus increasing the estimated risk to the point that the site is unacceptable. Or more information could demonstrate that there are few faults or fractures, and confirm that the site is acceptable. The risk hasn't changed, but the knowledge of the risk has changed, and this can affect decisions.

Predicting the future course of a carbon sequestration site is particularly challenging because the future stretches for such a long way: to be effective at limiting climate change, studies suggest that sequestration sites have to retain most of their CO_2 for at least several hundreds of years, and preferably thousands of years. These timescales are short compared to geologic timescales, but very long compared to the timescales over which deep subterranean phenomena have been monitored or predicted.

The ability to assess carbon sequestration sites will improve with time. Geologic monitoring technologies and methods improve, computer models improve in both temporal and spatial resolution and in their ability to handle new phenomena, geophysical understanding increases, and every year that passes provides another year of data from existing carbon sequestration sites. In short, the information needed to make decisions about site acceptability gets better with time and with experience.

The situation calls for adaptive decision-making:

- Start with sites, technologies, and actions for which the risk is believed to be acceptable now, even if this is a small list. As knowledge increases, the list will grow. Applying this principle may imply limited initial deployment of geologic carbon sequestration.
- In some cases, the information that can be gained from an action, or from using a certain site, may be an important criterion to consider, in addition to the probability of success. If two sites or technologies are judged to be acceptable in terms of risk and total cost, but one would provide information that the other would not, the one that provides new information should be considered. Especially in the early years, each sequestration site is not just a place to discard CO_2, it is also an experiment that will provide valuable data for use in future sequestration efforts.

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